ADVANCED ENGINEERING DELIVERS MORE EXACT WEAPONS

Laboratory engineers exploit new material compositions, manufacturing techniques, and high-performance computing to develop munitions that minimize collateral damage and improve near-field lethality.

IN times of war, military personnel rely on an arsenal of tools, gear, and weaponry. This armament is necessary for protecting troops in combat as well as for mounting an offensive against the opposition. In the 21st century, confrontations are increasingly more likely to occur in urban areas rather than battlefields. Advanced weapons capabilities allow troops to maneuver in tight, often densely populated areas while minimizing inadvertent casualties or destruction of infrastructure.

Beginning in 2010, Lawrence Livermore partnered with the Air Force Research Laboratory (AFRL), the Air Armament Center (AAC), and a Department of Defense (DoD) manufacturer to deliver a highly effective, low-collateral-damage munition known as BLU-129/B to the U.S. Air Force. As part of this joint effort, which received support from the Office of the Undersecretary of Defense for Acquisition, Technology, and Logistics, the Laboratory leveraged its long-term investments in computational codes, computing and manufacturing infrastructure, and engineering expertise to develop the munition in record time.

"Typically, the process for getting a new munition into the field is 4 to 6 years," says Livermore's Kip Hamilton, who managed the BLU-129/B project. "We had the first prototype in 9 months, and the warhead was completely fielded in 18 months." Hailed as a success by DoD, the munition has been contributing to military actions—and saving lives—ever since.

The Laboratory develops a broad range of conventional (nonnuclear) weapons-related technologies for DoD, including those implemented in BLU-129/B. Many of these technologies get their start through the Joint DoD/Department of Energy (DOE) Munitions Technology Development Program (JMP). Started in 1985 under a memorandum of understanding between DoD and DOE, JMP creates advanced technologies to meet warfighter needs. Lawrence Livermore

PERFORMANCE

A multidisciplinary team of Livermore weapons physicists, computational and materials scientists, and precision engineers contribute to development work for low-collateral-damage munitions. By combining computer modeling and experimental analysis, they evaluate a wide range of parameters, such as carbon-fiber type, winding patterns, tow tension, epoxy mix ratio, and curing cycle, to determine the most effective attributes to meet a sponsor's requirements. This photo shows (from left) Greg Larsen, Dan Schumann, Bob Sanchez, Scott Groves, Jim Matthews, and Stevan Mays as they lay down carbon-fiber strands over a fixed mandrel to produce a warhead case.

is one of three National Nuclear Security Administration laboratories that conduct the program's critical work in collaboration with military agencies. "We work closely with military personnel and DoD researchers to stay at the forefront of future weapon capabilities," say Lara Leininger, program manager for the Livermore JMP. "If we are doing our job right, we are accurately anticipating the department's needs. Then when DoD is ready to move forward with a new technology, we've done all the initial, high-level research, and it can be transitioned to the DoD service laboratories quickly."

Over the last decade, weapon design efforts have focused on creating munitions that more effectively channel energy onto an intended target and reduce collateral damage from impact debris. In addition to warhead technology, JMP research focuses on firing systems, computational mechanics and materials modeling, warhead applications, technologies to penetrate hard targets, and energetic materials. Currently, scientists and engineers are exploring how other materials, including novel composite metal materials, could be applied to future munitions to enable more customized functionality.

Speeding Up Weapons Development

In 2001, JMP began a suite of projects to study how the attributes of metal-loaded explosives could be used to produce a class of munitions that combine very low collateral damage with increased (near-field) lethality on a target. "The way wars are fought now is vastly different than it was even 15 years ago," says Hamilton. "More consideration is given to protecting warfighters in close proximity to targets and to civilians not engaged in the fight. Developing more exact weapons that produce few if any fragments and therefore reduce collateral damage is important to war efforts."

The JMP projects have shaped advances in computational modeling and simulation that leverage the Laboratory's high-performance computing (HPC) resources.

BLU-129/B improves near-field lethality in combat zones while reducing collateral damage.

Sophisticated models provide a reliable and validated predictive capability that researchers can use to analyze material compositions and characterize an explosive's properties.

"By adapting first-principles physics codes to run in parallel on high-performance supercomputers, we have greatly improved our understanding of critical interactions that can affect weapons performance," says Mike King, who leads the Multidisciplinary Modeling and Simulation Group in Livermore's Engineering Directorate. "As a result, we have been able to increase the attainable strength of composites, develop better manufacturing processes to build stronger joints, and significantly enhance our knowledge of the lethal mechanisms of munitions."

At the most fundamental level, conventional munitions have an internal explosive and an outer metal case surrounding the explosive fill. Typically, the case is made from steel—a strong, ductile, and durable material. "Metal munitions work the same way they have since black powder was invented in the 9th century," says King. "Put an energetic material in a metal tube, blow it apart, and fragments are ejected outward."

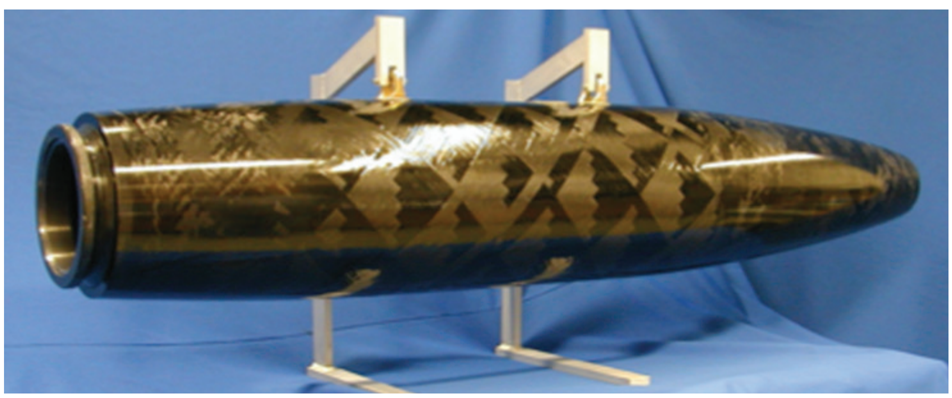
With munitions developed in the 20th century, a substantial amount of energy from the explosive goes into mechanically failing the case and accelerating the fragments. Fragments ejected from the case during detonation can travel long distances, often with lethal effects. As a result, the weapon can cause collateral damage outside the targeted area. JMP researchers began studying different material compositions with two goals in mind: eliminate the ejected fragments and improve the blast impulse at close range.

HPC resources were used to model a new type of explosive charge called multiphase blast explosive (MBX) and determine the appropriate volume needed for a munition. "Livermore's exploration of MBX performance properties began under JMP," says Dennis Baum, associate program director for Security Applications in the Laboratory's Weapons and Complex Integration Principal Directorate. Prior to Lawrence Livermore's involvement, researchers at AFRL and its High Explosive Research and Development Facility evaluated MBX as part of an effort to improve the effectiveness of existing penetrator weapons. Those exploratory tests revealed that a target subjected to an MBX charge experienced a greater impulse of energy than did targets subjected to other explosive compositions. "MBX fundamentally changed the rate at which lethality decreases with distance from the munition," says Baum. "It was the key enabling technology that eliminated the need for a metal case."

Livermore's growing expertise in modeling and fabricating composite materials such as carbon fiber was an important part of the Air Force partnership. Composites are made from two or more chemically and physically different materials that when combined can be "tailored" to deliver specific effects. To create a munition that could meet the sponsor's low-collateral-damage requirements, the project team created a composite outer shell to use with the novel MBX fill.

Carbon-fiber composite is a well-studied material and is widely used in industrial applications, such as in aircraft and automobile components. In certain configurations, it can be stronger than steel at a fraction of the weight. The composite's precise characteristics can also be controlled by the pattern in which the fibers are wound. A carbon-fiber composite case has the strength to withstand penetration into concrete structures and produces no lethal fragments on detonation. The total system weight is also greatly reduced.

The Laboratory's HPC capabilities help researchers optimize designs for carbon composite cases and meet the



Carbon-fiber composite cases, such as the one shown here, produce no lethal fragments when the munition is detonated. They also weigh much less than conventional steel cases.

sponsors' stringent operational and performance requirements. Computing codes model fundamental material properties and simulate composite performance under extreme conditions, for example, assessing material behavior up to and after failure. "As part of the JMP effort, we are exploring the basic failure mechanisms of composites under compression so we can design stronger materials," says King.

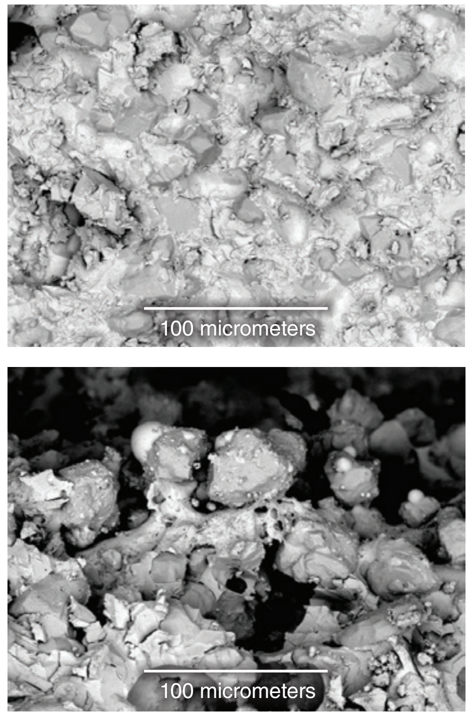
Carbon-fiber composite is strong, but it can fracture when compressed. This type of failure, known as microbuckling, occurs when the fibers locally buckle and then form kink bands. Computational tools such as the carbon micromechanical model serve as a test bed for subjecting virtual materials to an array of external conditions before experiments are run to confirm the results.

Simulations also greatly reduce the cost and time needed to design a weapon. "In the 'old' days, we would build a prototype, test it, and revamp it based on the results," says Hamilton. "We had to complete many cycles of testing before we had a production-ready component. Our advanced modeling and simulation capabilities reduce the time needed to determine the final design specifications for munitions. For example, 95 percent of the final design for BLU-129/B was done through modeling and simulation." King and Hamilton note that even with advanced computing capabilities, experimental testing is still needed to validate models. Says King, "Experiments provide an affirmation that new munitions will perform exactly as intended."

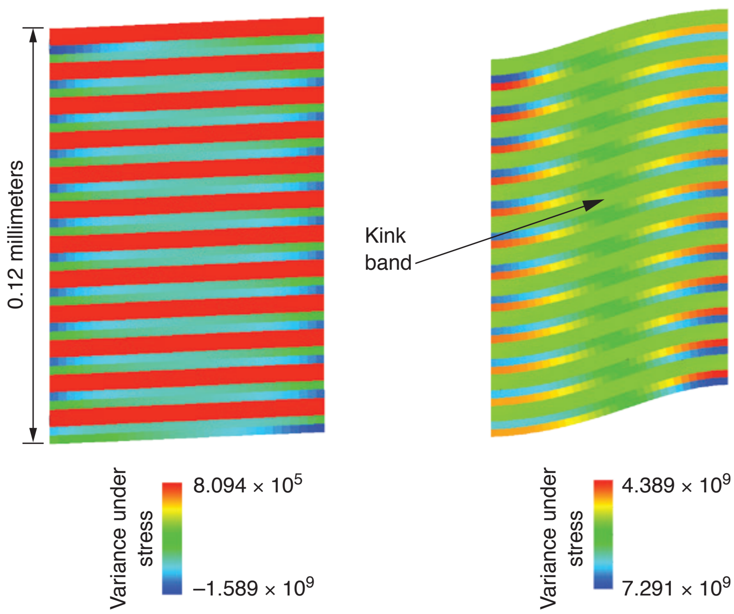
Weapon Functionality on the Fly

In a separate JMP project, Livermore scientists and engineers are developing new metal material compositions to further tune weapon effects. "We are working on conceptual technology that could be applied to future munitions," says Livermore materials scientist and engineer Mukul Kumar, who leads this project. His team is studying multicomponent materials with microstructures that exploit the different responses of each component. The team's goal is to fabricate novel material compositions that customize fragmentation of a warhead case. "We intend to develop robust, affordable, and well-understood materials by properly engineering their microstructure to produce predictable fragments," says Kumar. "Essentially, we are enabling fragmentation by design."

Metal cases for warheads generally fragment in one of two ways: naturally or in a controlled manner. Natural fragmentation, which has been extensively studied, yields a random distribution of particle sizes. In controlled fragmentation, the case is mechanically scored to produce a particular size distribution. Developing designer, engineered case materials with "tailored lethality" for natural fragmentation (including materials that produce no fragmentation) requires knowing how a material's structure and properties influence case breakup. Says Kumar, "To determine how a material's microstructure affects its dynamic properties, scientists and engineers must understand both the



Micrographs reveal microstructural details of a composite material (top) before and (bottom) after compression tests. Light regions are the matrix material, and dark regions are metal designed for tailored fragmentation. After compression, the microstructure clearly shows that the matrix material was removed.



Results from a carbon micromechanical simulation illustrate how compression causes a material's fibers to buckle and form kink bands.

fundamental physics of the natural length scale in fragmentation and the coupling of the microstructure to these conditions."

As a proof of concept, Laboratory investigators Kyle Sullivan and Joshua Kuntz in the Physical and Life Sciences Directorate are creating and testing powder composites of metals intended to become fragments combined with a matrix material. "We chose materials that have the strength, toughness, and ductility needed for the applications we are interested in," says Kumar.

Sullivan worked with physicist Damian Swift on laboratory-scale experiments to help validate powder metallurgy techniques and material response—spalling or cracking, for example—of microstructures across a broad range of material volumes. The tests confirmed that the engineered microstructures respond as expected. The matrix material can be manipulated, leaving behind high-density particles. Understanding how metallic composites transform under these conditions is key to developing a composition and microstructure that deliver a desired fragmentation response.

"Conducting lab-scale tests as preliminary experiments has been valuable," says Kumar. "They can be readily fielded and provide the conditions necessary to validate our compositions. We can also easily remove samples for postshot analysis, and the throughput is excellent, allowing us to run 5 to 10 samples a day." If initial tests confirm the predicted behavior, another set of experiments will be conducted on a larger scale to perfect the composite. These final tests will determine whether the material developed is viable for fragmenting a case as designed. Kumar says, "Tailoring the fragmentation response of warhead case materials will enable a broad range of selective effects munitions."

Modeling and simulation efforts run parallel to the characterization and testing of these novel microarchitectures. The first objective of the computational work is to build a robust framework for performing calculations on fragmenting metals.

In 2012, Livermore researchers James Stölken and Matthew Barham simulated a particular type of steel and used the resulting data to determine the constitutive parameters for Livermore hydrocodes. The experimental work, from an earlier JMP-funded collaboration with the U.S. Army Armament Research, Development, and Engineering Center and Sandia National Laboratories, probed the effect of a systematic variation in a material's microstructure. "This work has served as a terrific test bed for simulation capabilities," say Kumar. The same tools are being used to study the metal powder composites in the current JMP project. "These tools may one day enable us to computationally design material microstructures and architectures for specially tailored response in munitions."

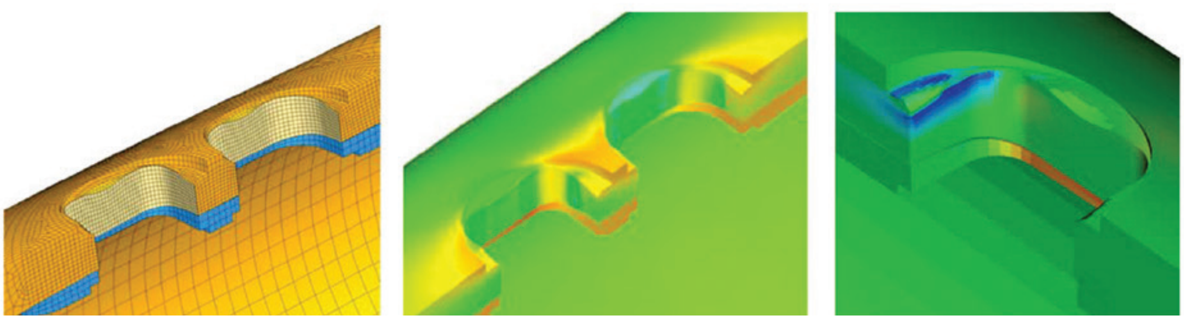
Alternative processing routes and material fabrication are also being evaluated. In the future, advanced additive manufacturing techniques could enable an entirely new class of material structures with improved performance. (See *S&TR*, March 2012, pp. 14–20.)

Target Precisely Acquired

When developing a munition, computational and weapons engineers must be familiar with the system requirements designated by the sponsor. Engineers must also assess the potential limitations, including whether possible contaminants could affect a munition's operability and what level of damage could ultimately cause it to fail. Mitch Moffet, a Livermore weapons engineer says, "We have to deliver exactly what the sponsor wants and needs, which requires a thorough understanding of how the weapon can and will perform." Computational and weapons engineers must work in tandem throughout the design process to ensure that what is created in theory through models and simulation can actually be built. Adds Moffet, "The two disciplines iterate back and forth until we have a workable design."

New munitions must be compatible with existing guidance systems, which have become exceedingly accurate in recent years and have made it possible to build more effective weapons. "Old munitions, such as the ones used in World War II, are like a shotgun. They are designed to work even when a target cannot be pinpointed directly," says King. "With precision guidance, warfighters aren't limited to using weapons with a large range of effectiveness because the laser can more accurately acquire a target."

The ability to couple sophisticated guidance systems with weapons that have a more accurate lethal footprint has been profound. By making the effects of weapons commensurate with their



Supercomputing models and simulations allow engineering features in the composite case to be optimized to maximize strength and performance.

accuracy, engineers are providing the military with highly efficient and effective munitions for fighting in close quarters.

A Win–Win Situation

The JMP–Livermore partnership has a proven track record for executing exceptional weapons science in service to the nation. BLU-129/B is an important example of this tradition. One issue that has plagued munition development is the speed at which weapon technology is transferred from government to industry and thus from a laboratory to the military. Typically, researchers design and test a munition and transfer the specifications to a manufacturer, whose team redesigns the munition based on the detailed parameters. These new revised units must also be tested, increasing costs and delaying delivery of the final system.

The seamless transition from BLU-129/B concept to deployed munition illustrates the benefits of a close collaboration with the sponsor and the manufacturer. “Throughout the entire program, we included the manufacturer in the warhead development and assembly processes to ease the transition from Livermore’s warhead prototypes to industrial production,” says Hamilton. The Livermore team designed, built, and provided the manufacturer with most of the tooling required to assemble the system. As a result, the production units were assembled using the same tools and methodologies that the Laboratory team put together during the project’s development phase.

Prior to assembling production units of BLU-129/B, Livermore collaborated with AFRL to test the munition’s durability and reliability. Researchers subjected the munition to a complete battery of tests, including those for flight safety. In one set of experiments, a bomb dropped from significant height came out unscathed, demonstrating its safety. Another experiment chilled a munition to the incredibly low temperatures found at high altitude and then shot it through a concrete wall. Says King, “We learned that these munitions can withstand many types of physical hardships and still function as designed.”

Vibrational testing with a modal device is used to validate guidance kit functionality and ensure that munitions will perform as designed. Lugs are installed into wells on a munition so it can be directly attached to the test apparatus or to an aircraft once it is approved for deployment.

Another benefit of the LLNL–AFRL–AAC partnership is that BLU-129/B is a government-owned design. As a result, the contract to manufacture production units can be put up for bid to other industrial companies as a means to reduce production costs for the military. Overall, the technology-transfer process was a win–win for the armed services: production units function as designed, and the system is cost-effective.

The BLU-129/B project is a prime example of what can be achieved when multidisciplinary teams from several institutions work toward a common goal with strong support from each organization’s management and from the project’s sponsors. “To meet the needs of this time-critical mission, Livermore’s senior management ranked the project as high priority and supported the team throughout the design and development process,” says Hamilton. “We were able to tap systems engineering expertise to rapidly assemble key personnel across multiple engineering divisions and implement needed facility capabilities.”

He recalls that at one point, the team had to resurrect an old press from storage to test compression parameters for the munition. “It was the only press that could provide the pressures needed for the test.” With a little elbow grease and engineering know-how, the team had the press up and running in time for the necessary experiments.

Hamilton, Moffet, and King agree that the Laboratory’s partnerships with its sponsors and industry plus the tenacity and vision of the entire development team were important for the project’s success. As a result, the military could deploy a new unit for flight certification in the same calendar year that the project started. “We contributed to saving lives in the combat zone in 18 months,” says Moffet. It was an impressive feat by any standard, and one that is enabling warfare to be fought with better precision while helping to protect soldiers and innocent civilians.

The success of BLU-129/B serves as a blueprint for future research, technology transfer, and engineered munitions at the Laboratory. Says Leininger, “When we combine this blueprint with the continuing development of munitions technologies in JMP, the possibilities for transitioning advanced munitions to meet warfighter needs is unlimited.”

—Caryn Meissner

Key Words: Air Armament Center (AAC), Air Force Research Laboratory (AFRL), BLU-129/B, carbon fiber, composite material, Department of Defense (DoD), Department of Energy (DOE), Joint DoD/DOE Munitions Technology Development Program (JMP), multiphase blast explosive (MBX), munition, weapon.

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